Clinical experience with epidural cooling for spinal cord protection during thoracic and thoracoabdominal aneurysm repair

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Purpose: This report summarizes our experience with epidural cooling (EC) to achieve regional spinal cord hypothermia and thereby decrease the risk of spinal cord ischemic injury during the course of descending thoracic aneurysm (TA) and thoracoabdominal aneurysm (TAA) repair.

Methods: During the interval July 1993 to Dec. 1995, 70 patients underwent TA (n = 9, 13%) or TAA (n = 61) (type I, 24 [34%], type II, 11 [15%], type III, 26 [37%]) repair using the EC technique. The latter was accomplished by continuous infusion of normal saline (4° C) into a T_{11-12} epidural catheter; an intrathecal catheter was placed at the L_{3-4} level for monitoring of cerebrospinal fluid temperature (CSFT) and pressure (CSFP). All operations (one exception, atriofemoral bypass) were performed with the clamp-and-sew technique, and 50% of patients had preservation of intercostal vessels at proximal or distal anastomoses (30%) or by separate inclusion button (20%). Neurologic outcome was compared with a published predictive model for the incidence of neurologic deficits after TAA repair and with a matched (Type IV excluded) consecutive, control group (n = 55) who underwent TAA repair in the period 1990 to 1993 before use of EC.

Results: EC was successful in all patients, with a 1442 ± 718 ml mean (range, 200 to 3500 ml) volume of infusate; CSFT was reduced to a mean of 24° ± 3° C during aortic cross-clamping with maintenance of core temperature of 34° ± 0.8± C. Mean CSFP increased from baseline values of 13 ± 8 mm Hg to 31 ± 6 mm Hg during cross-clamp. Seven patients (10%) died within 60 days of surgery, but all survived long enough for evaluation of neurologic deficits. The EC group and control group were well-matched with respect to mean age, incidence of acute presentations/aortic dissection/aneurysm rupture, TAA type distribution, and aortic cross-clamp times. Two lower extremity neurologic deficits (2.9%) were observed in the EC patients and 13 (23%) in the control group ($p < 0.0001$). Observed and predicted deficits in the EC patients were 2.9% and 20.0% ($p = 0.001$), and for the control group 23% and 17.8% ($p = 0.48$). In considering EC and control patients (n = 115), variables associated with postoperative neurologic deficit were prolonged (>60 min) visceral aortic cross-clamp time (relative risk, 4.4; 95% CI, 1.2 to 16.5; $p = 0.02$) and lack of epidural cooling (relative risk, 9.8; 95% CI, 2 to 48; $p = 0.005$).

Conclusion: EC is a safe and effective technique to increase the ischemic tolerance of the spinal cord during TA or TAA repair. When used in conjunction with a clamp-and-sew technique and a strategy of selective intercostal reanastomosis, EC has significantly reduced the incidence of neurologic deficits after TAA repair. (J Vasc Surg 1997; 25:234-43.)

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Spinal cord ischemic injury during the course of thoracic and thoracoabdominal aneurysm repair remains an unsolved problem. In the largest single institutional experience reported, Svensson et al.[1] summarized Crawford's data with more than 1500 patients and reported an overall incidence of spinal cord injury of 16%, approximately half of which were devastating paraplegia. Patients who sustain this degree of spinal cord damage have excessive perioperative and late mortality rates. Although there is general agreement that the clinical variables of aneurysm extent, aortic cross-clamp times, operation for rupture, and aortic dissection greatly influence the risk of this complication, there is no consensus on the optimal strategy to minimize its risk. Indeed, the multiplicity of surgical and nonsurgical adjuncts currently in use is adequate testimony to the fact that no single method has been either proven effective or universally applied. Rather, individual surgeons and institutions have adopted methods that in particular environments have proven effective in reducing spinal cord injury when compared with historical, institutional controls. These include distal perfusion (atriofemoral bypass) with cerebrospinal fluid (CSF) drainage,[2] intravenous naloxone and CSF drainage,[3] profound hypothermia with circulatory arrest,[4] and moderate systemic hypothermia with atriofemoral bypass.[5]

Among those adjuncts designed to prevent spinal cord injury, the concept of regional hypothermia seemed particularly suited to our system for management of patients with thoracoabdominal aneurysms (TAA). We believe maintenance of core temperature to be an important component of intraoperative management.[6] In addition, substantial experimental data indicate that regional hypothermia is protective against spinal cord ischemic damage in several animal models of aortic cross-clamp–induced cord injury.[7-12] Extrapolating from the animal work of Marsala et al.,[8] we devised a method for providing regional hypothermia to that segment of the spinal cord at risk for ischemic injury during TAA repair.[13] We report experience with this technique in 70 patients over a 2½-year period and demonstrate its favorable impact on the incidence of lower extremity neurologic complications after TAA repair.

PATIENTS AND METHODS

During the interval July 1993 to January 1996, 70 consecutively treated patients with thoracic aneurysms (TA) or types I, II, or III TAA were managed with adjunctive use of intraoperative epidural cooling. The study was approved by the Massachusetts General Hospital Committee on Human Studies, and no patient refused to participate. Type IV TAA patients were excluded because of perceived low risk for ischemic spinal cord complications.

Table I. Demographic and clinical data for 70 patients managed with EC

		n (%)
Mean Age (yr)	70 ± 11	
Range	30 to 85	
Familial history aortic aneurysm		7 (10)
Diabetes		5 (7)
Serum creatinine level ≥1.5 mg/dl		19 (27)
Aneurysm extent		
Type I		24 (34)
Type II		11 (15)
Type III		26 (37)
Descending thoracic		9 (13)
Pathologic characteristic of aneurysm		
Degenerative		55 (78)
Dissection		13 (19)
Mycotic		1
Inflammatory		1
Patients with prior aortic resections		31 (44)
Infrarenal AAA	25 (80)	
Thoracoabdominal	4 (13)	
Proximal thoracic aorta	6 (19)	
Clinical presentation		
Elective operation		55 (78)
Urgent operation		15 (21)
Rupture		8 (11)

Aneurysms were classified according to the scheme devised by Crawford et al.[14] In types I and II TAA, the entire descending thoracic aorta was resected. Eight of nine TA involved half or more of the descending thoracic aorta. Clinical and demographic data referable to the study group are detailed in Table I. Four patients with dissecting aneurysms had Marfan syndrome. Thirty-five prior aortic aneurysm resections were performed in 31 patients (44%). Three of these patients had multiple prior aortic resections. Additional antecedent vascular operations included an axillobifemoral bypass that was converted to anatomic replacement in the course of TAA resection, femoropopliteal bypass (4), carotid endarterectomy (4), and coronary artery bypass grafting (7). Urgent or acute operation/presentation was defined as either rupture or presentation with acute back/abdominal pain that necessitated ICU observation and operation within 24 hours of admission. All patients with ruptured aneurysms were hemodynamically stable on transport to the operating room.

Surgery was performed (with a single exception) with a clamp-and-sew technique without administration of systemic heparin. In a single patient with Marfan syndrome, atriofemoral bypass was used for

Table II. Patient characteristics

Variable	*Epidural cooling (n = 70) 1993-1995*	*Control (n = 55) 1990-1993*	*p*
Mean age (yrs) (range)	70 (30 to 85)	70± (35 to 88)	0.82
Type I/II TAA (%)	50	38	0.14
(%) Acute presentation or dissection	34	30	0.69
Visceral aortic cross-clamp time, mean (range) in min	48 (28 to 94)	46 (22 to 90)	0.34
Preservation/reimplantation intercostal vessels (%)	50	33	0.04
T_8-L_1 intercostal vessel sacrificed (%)*	44	34	0.345
Prior aortic graft(s) (%)	44	27	0.016
% with creatinine level ≥1.5 mg/dl	27	35	0.372

*Oversewing of at least one pair intercostal vessels in T_8-L_1.

the second stage (type I TAA) of an elephant trunk procedure. Perfusion of the renal arteries with a solution of iced (4° C) Ringer's lactate with methylprednisolone (1 gm/L) and mannitol (25 gm/L) was performed in cases where the renal arteries were accessible. Mannitol and furosemide were administered before aortic cross-clamping. In general, a selective approach to intercostal vessel reimplantation was followed. Patent intercostal vessels in the T_8-L_1 region were reimplanted by separate inclusion button or preserved at anastomotic regions whenever technically feasible. Operative death was defined as any death occurring within 60 days of surgery. Pulmonary complications were considered major in any of the following circumstances: (1) mechanical ventilation more than 72 hours after surgery; (2) pneumonia verified by chest radiogram; (3) return to intensive care unit for respiratory causes; (4) reintubation. Renal-related complications were considered minor when nonoliguric and with a postoperative serum creatinine level two times baseline values or less.

Anesthetic management was supervised in each case by a dedicated vascular anesthesia team (JKD). The specifics of the epidural infusion system have previously been described in detail[13]; the principle components include placement of a 4F 40 cm catheter at the T_{11-12} epidural interspace, which is advanced cephalad 4 to 5 cm. This catheter is used both for administration of local anesthetic and for infusion of iced (4° C) normal saline. A second 4F thermistor catheter is placed 4 cm into the subarachnoid space at the L_{3-4} interspace, permitting both continuous recording of CSF temperature and pressure. The epidural cooling infusion is begun in anticipation (mean, 74 minutes; range, 17 to 240 minutes before) of aortic cross-clamping. Pharmacologic afterload reduction with Na nitroprusside is used routinely before cross-clamp, and infusions of $NaHCO_3$ are used until the visceral vessels are perfused. No dextrose solutions were used.

To assess the impact on neurologic complications over time at our institution, data were gathered retrospectively on a consecutive cohort of patients with TA/TAA treated at our institution during the interval 1990 to 1993, immediately before adoption of the epidural cooling system. Patients with type IV aneurysms and those not surviving sufficiently long (n = 25 patients) to permit postoperative evaluation of lower extremity neurologic status were excluded. Important clinical characteristics that can potentially influence the risk of spinal cord injury for both the epidural cooling (EC) and control patients are presented in Table II. Although there was increased use of intercostal reanastomosis of borderline ($p = 0.04$) significance in the EC patients, this group also had significantly more prior aortic grafts and a higher percentage (50% vs 38%) of more extensive type I/II aneurysms. Aneurysm distribution in the control group was thoracic, 18%; type I, 22%; type II, 16%; and type III, 44%.

Results with respect to neurologic deficits were compared for EC versus control patients with Pearson χ^2. Logistic regression was used to identify variables independently associated with postoperative neurologic deficit, and in this analysis the entire 1990 to 1995 experience was considered to examine a sufficient number (n = 15) of deficits. Results were also compared with the expected incidence of neurologic events using the predictive model developed by Acher et al. This model includes the variables aneurysm extent (Crawford classification), acute clinical presentations (overtly symptomatic or ruptured), and the presence of aortic dissection as its principle components, and was previously validated by the demonstration of a strong (0.997) correlation coefficient between the observed and predicted incidence of deficits in 16 published series of TAA repairs.[3]

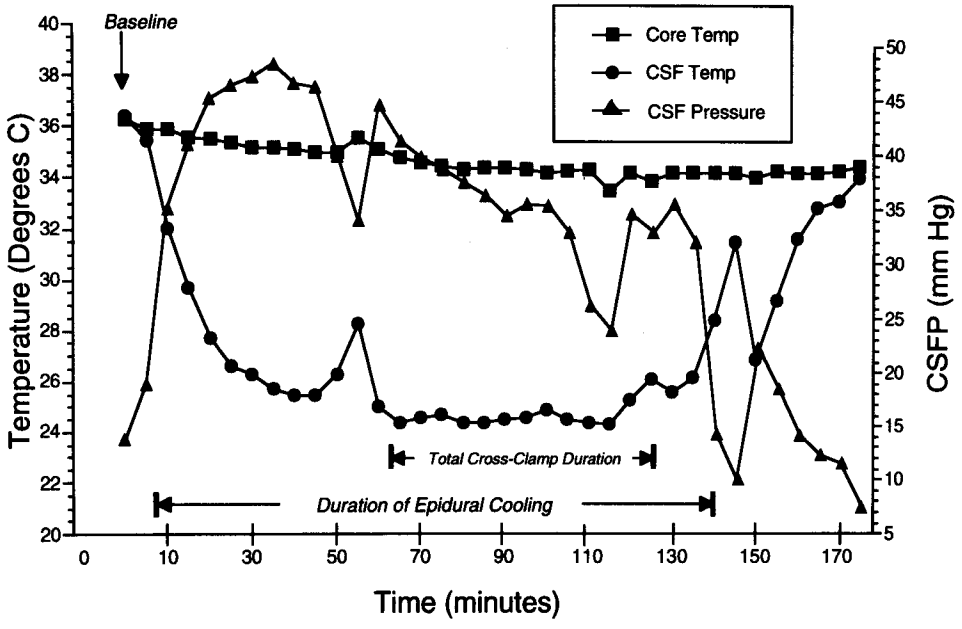

Fig. 1. Graphic display of mean data from 70 patients for CSF temperature and pressure, along with core temperature during conduct of operation. Total cross-clamp duration refers to interval until reperfusion of legs.

Table III. CSF temperature and pressure—EC period

	Baseline ± SD	*Before cross-clamp*	*During cross-clamp*	*1 hr after cross-clamp removal*
Core temperature (° C) mean (range)	36 ± 0.5	35 ± 0.3 (34 to 35)	34 ± 0.2 (33 to 35)	34 ± 0.1
CSF temperature (° C) mean (range)	36 ± 1.0	28 ± 3 (24 to 35)	25 ± 1 (24 to 28)	32 ± 0.9 (31 to 34)
CSF pressure (mm Hg) mean (range)	13 ± 8	40 ± 8 (18 to 46)	31 ± 6 (24 to 44)	11 ± 2 (8 to 14)

RESULTS

Operative management. Epidural infusion volumes averaged 1409 ml (range, 200 to 3500 ml) and varied with the complexity of the repair. Resultant effects on CSF temperature and pressure are presented in Table III and Fig. 1. In two patients, mechanical problems with the epidural catheters required supplementation with subarachnoid infusions via the intrathecal catheter. During the period of aortic cross-clamp, mean CSF temperature was reduced to 25° ± 1° C. Aortic cross-clamp times varied in accordance with the complexity of the repair. Visceral ischemic times (time until perfusion celiac/right renal and superior mesenteric artery) averaged 48 minutes (range, 28 to 94 minutes), and mean cross-clamp time until reperfusion of the legs was 64 minutes (range, 23 to 122 minutes). Mean visceral ischemic times in types I and II aneurysms were 51 minutes (range, 30 to 94 minutes) as opposed to 44 minutes (range, 28 to 75 minutes) in type III TAA and TA.

Management of patent intercostal vessels was aggressive, with 51% of patients having patent vessels either preserved in beveled proximal or distal aortic anastomoses (21 patients) or reconstructed with a separate intercostal inclusion button (16 patients; one patient had both). The latter maneuver was generally performed only in patients with types I and II aneurysms. However, 30 patients (44%) had sacrifice of at least one pair of intercostal vessels in the T_8-L_1 region, that is, few patients had preservation of all patent intercostal vessels in the critical T_8-L_1 zone.

Operative results. Major operative complications for the EC group are displayed in Table IV. All patients who died survived long enough for at least an initial observation for neurologic deficits, and one deficit occurred in these patients (see below). Intervals between operation and death were 5 days (one

Table IV. Operative morbidity in 70 patients managed with EC

Complication	*n (%)*
Death	7 (10)
Mesenteric ischemia (1)	
Respiratory and multiple organ failure (4)	
Myocardial infarction (1)	
Rupture proximal aneurysm (1)	
Pulmonary	18 (25)
Major (10)	
Minor (8)	
Cardiac	4 (6)
Renal	10 (14)
Minor (8)	
Dialysis (2)	
Stroke	3 (4)

Table V. Neurologic deficits

Group	*n*	*Observed*		*Predicted**
EC	70	2 (2.9%)	$p = 0.001$	14 (20%)
	$p < 0.0001$			
Control	55	13 (23.2%)	$p = 0.48$	10 (17.8%)

*Using model Acher et al.[3]

patient), 1 week (three patients), 2 weeks (two patients), and 5 weeks (one patient). Of three patients who had a perioperative stroke, only one had a persistent major deficit (arm monoplegia) at discharge. The operative mortality in control patients (1990 to 1993) was five of 55 (9%).

Lower extremity neurologic deficits. Two neurologic deficits occurred in the 70 EC patients. One patient with a type III TAA awoke with a profound proximal cord injury manifested by bilateral upper extremity paraplegia with preservation of leg motion. This patient died 7 days later of multisystem organ failure, and at autopsy had histologic documentation of ischemic damage in the cord from C_3-T_4. Anterior and posterior spinal arteries were normal, as was the remainder of the cord from T_5 to lumbosacral levels. This patient had sustained intraoperative hypotension that required vasopressor support before and during the initial stages of the epidural infusion. A second patient with a type I TAA developed a Brown-Séquard type of cord injury 72 hours after surgery that clinically manifest as unilateral leg weakness. This patient had sacrifice of multiple patent intercostal vessels at $T_{9\text{-}12}$. Excessive calcific atherosclerosis surrounding these vessels precluded safe intercostal reanastomosis. Full recovery with independent ambulation was seen within 2 months of surgery. In the control group 13 deficits (23%) occurred. Eight of these were total paraplegia, and all were noted as the patients awoke from anesthesia. Five of these eight devastating deficits occurred in patients with type I (one patient) or II (four patients) aneurysms. The other five deficits were paraparesis, three of which occurred early and two delayed. Differences between observed/predicted deficits between EC patients and controls are displayed in Table V. If the entire experience with 115 patients is considered, variables examined for association with postoperative neurologic deficits are displayed in Table VI. After logistic regression analyses, only a prolonged visceral aortic cross-clamp time (>60 minutes), with a relative risk of 4.4 (95% CI, 1.2 to 16.5; $p = 0.02$), and lack of epidural cooling, with a relative risk of 9.8 (95% CI, 2 to 48; $p = 0.005$), were significantly and independently associated with development of a postoperative neurologic deficit.

DISCUSSION

At our institution, the adoption of EC for spinal cord protection has been accompanied by significant reduction in lower extremity neurologic deficits after TAA repair. The rationale for this method is to increase the ischemic tolerance of the region of the cord that is most susceptible to ischemic injury (i.e., the lower thoracic lumbar cord) during the critical period of aortic cross-clamping when relative spinal cord perfusion pressure is reduced. Based on observations in patients with recordings of somatosensory evoked potentials, we observed the hypothermic effect to be regional, that is, limited to the lower thoracic and lumbar cord. Somatosensory evoked potentials in the legs were obliterated as expected because of the hypothermic mileau, whereas those recorded in the arms were unaffected.[15] Furthermore, the CSF temperature rapidly approaches baseline after discontinuation of the infusion consistent with the expectation that the perfusate rapidly exits the epidural space along nerve root tracks. Thus the hypothermic effect is both regional along the cord, and the epidural infusion has no significant effect on core temperature. Maintenance of near-normal core temperature homeostasis is an important component in minimizing fluid shifts, coagulopathy, and the potential for cardiac rhythm disturbance.[6]

Among the surgical and nonsurgical adjuncts promulgated for their spinal cord protective benefit and reviewed elsewhere,[16] hypothermia was particularly appealing to us. Impressive results with a variety of animal models,[7-11] the experience with profound

hypothermia for repair of complex cardiac and aortic arch disease, and a commitment to an expeditious operation without distal perfusion have led to this posture. The practical consideration of the degree of hypothermia necessary for protection has only recently been answered. It has been demonstrated that regional, profound (15° to 18° C) hypothermia was uniformly protective in a dog model of cross-clamp–induced cord injury.[7,12] However, the open laminotomy technique required to achieve this degree of hypothermia is not clinically applicable. Thereafter, Marsala et al.[8] and subsequently Gonzalez-Fajardo et al.[11] demonstrated that moderate (25° to 27° C) regional hypothermia was also uniformly protective. These investigations have used epidural infusion systems quite similar to that reported herein for clinical use. Other methods for achieving regional hypothermia via intravascular infusion have required infusion into excluded segments of the aneurysm sac.[17,18] In addition to expending cross-clamp time, such methods necessarily rely on patent intercostal vessels for ultimate delivery of the infusate to the cord, and the degree of cord hypothermia achievable with this intravascular route has not been verified. Finally, even when profound hypothermia and circulatory arrest (intrathecal temperature, 15.6° C) has been applied in patients with TAA, overall results do not compare favorably to those achieved in the present series.[4]

Overall results in the present series can be cited as comparable with those achieved in some centers,[2-4] but improved when compared with other contemporary reports.[19,20] The operative mortality rate remains in the 10% range, not significantly different from our earlier experience.[21] Half of the perioperative deaths resulted from multisystem failure, with respiratory decompensation being the principle contributor to this cascade. Others have emphasized the importance of pulmonary morbidity associated with this operation.[22] Cardiac-related death and significant renal failure have been uncommon in recent practice. The two patients who required postoperative dialysis had stable early postoperative renal function, and dialysis was instituted after the cascade of multisystem failure began; both patients died.

Neurologic deficits decreased dramatically in patients who were managed with epidural cooling. The 2.9% deficit rate in patients so managed compares favorably with the bulk of prior reported experience.[1-5,14,18-21] However, comparisons with other reports are difficult because patient groups and definitions of aneurysm extent and what is classified as an "acute" aneurysm or even "dissection" may vary. We have continued to apply the designation type II aneurysm as involving the entire descending aorta, whereas others have liberalized the extent wherein a TAA may be designated "type II."[2,3] Nearly half of the patients of Acher et al.[3] were designated "acute" aneurysms, but only 34% of our patients could fairly be classified as acute and/or dissection. These distinctions may seem semantic, but because such designations do figure prominently in the prediction of neurologic deficits from the Acher model, they are important to emphasize. We agree with the consensus that TAA extent, dissection as the pathologic mechanism, rupture, and cross-clamp times are the important variables in predicting risk of neurologic deficit.[1,4] Yet the material presented herein only verified the variables of prolonged cross-clamp time and lack of EC as independently associated with deficit risk (Table VI). It is likely that the low overall deficit rate of 13.5% since 1990, and the elimination of the lowest risk patients (type IV TAA) explains these findings. Although significance was not seen for the parameters of aneurysm rupture and extent, deficits occurred twice as often in patients with rupture, and five of eight total paraplegia deficits occurred in patients with type I or II aneurysms. Given the shortcomings of comparisons with other reports, the more impressive data relate to our own historical control group. We agree with Acher et al.[3] that contemporary reports may appear overly optimistic when compared with historical controls where deficit rates may be unusually high. In our own material, there was good correlation between the predicted and observed deficit rate in the control patients.

A significant limitation of the EC technique is the

Table VI. Univariate analysis of variables examined for association with postoperative neurologic deficit, 1990 to 1995

	Paraplegia/paraparesis		
Variable	*No (n = 110) n (%)*	*Yes (n = 15) n (%)*	*p*
Age >70 years	61 (55)	8 (53)	0.877
Creatinine level ≥1.8 mg/dl	17 (15)	3 (20)	0.652
Prior aortic graft	41 (37)	3 (20)	0.243
Type I/type II TAA	48 (43)	8 (53)	0.479
Acute presentation/ dissection	35 (31)	6 (40)	0.527
Rupture	14 (12)	4 (26)	0.113
Intercostal preservation/ intercostal reimplant	48 (44)	6 (40)	0.790
Cross-clamp time >60 min	17 (15)	6 (40)	0.021
Use of EC	68 (61)	2 (13)	0.0001

rise in CSFP coincident with EC. Although CSF drainage continues to be an important adjunct to control rises in CSFP coincident with cross-clamping, experience to date with CSF drainage alone has been disappointing.[23,24] We recorded a threefold increase in CSFP during the initial phases of cooling, which we accepted because it occurs before cross-clamping. However, an approximate doubling of CSFP does occur during the period of cross-clamping. Because the vulnerable segment of the cord is at 25° C at this point in the operation, the neuroprotective effect of the regional hypothermia appears to outweigh the potential disadvantages of increased CSFP. Because there is no definitive information (in patients) on the dynamics of relative spinal cord perfusion pressure and its relation to CSFP, we maintain an arbitrary 30 mm Hg gradient between mean arterial and CSFP during the infusion. Furthermore, the CSFP tracing is observed continuously for damping, which will occur at higher levels of CSFP. Control of CSFP during the infusion can be achieved by CSF withdrawal, or tapering the infusion. We cannot exclude the possibility that increased CSFP contributed to the very unusual but devastating lower cervical/upper thoracic cord injury that occurred in a single patient.

Among other intraoperative maneuvers relative to the risk of ischemic cord injury is the management of patent intercostal vessels. We have maintained an aggressive posture towards intercostal reanastomosis in the critical T_8-L_1 region, and some 64% of current patients with patent vessels in this region had reconstruction of these vessels, which may have contributed to the improved results in patients managed with EC. The detailed studies of intercostal vessels by Svensson et al.[25] provided circumstantial evidence of the importance of intercostal preservation, but when performed as a "stand alone" adjunct paraplegia rates were still distressingly high. Recent reports with intraoperative direct epidural evoked potential monitoring have provided, in our view, the best evidence to date of the worth of intercostal reanastomosis.[26,27] A significant and unanswered question has been whether such reconstruction can be performed rapidly enough. With the provision for regional hypothermia afforded by the EC technique the ischemic tolerance of the cord is extended until such point where its principle (by intercostal reanastomoses) or collateral (by removal of cross-clamp) circulation can be reestablished. Whether all intercostal vessels can be sacrificed and the cord adequately supplied by collateral circulation with the use of other neuroprotective agents such as Naxolone remains unknown.[3] We agree with Acher et al. that the "sump" effect of freely backbleeding or patent intercostal vessels can potentially "steal" relative spinal cord perfusion pressure during cross-clamp. We immediately oversew the typically vigorously backbleeding intercostal vessels in the T_4-T_7 region, in addition to those not selected for reconstruction in the T_8-L_1 region. Vessels selected for reconstruction in the latter region are promptly balloon-occluded until reconstructed and reperfused.

Despite the favorable experience with EC reported herein, the threat of ischemic cord injury with TAA repair persists. The EC technique is a maneuver directed at a specific cord region and point in time, namely ischemia during cross-clamp. No comment can be made about the utility of this method in environments where intercostal vessels are routinely sacrificed or partial bypass techniques are used. The principal impact of EC in our practice has been referable to the immediate total paraplegic deficit. To the extent that delayed deficits can be caused by thrombosis of reconstructed intercostal vessel, cord swelling, or hemodynamic shifts in the postoperative period, there is little reason to believe that EC in the operating room will favorably affect these events. Our data have demonstrated that an approximate doubling of CSFP during cross-clamp can be tolerated with the provision of regional hypothermia, but the rise in CSFP remains the principal limitation with respect to the mechanics of EC. Further evaluation of EC in other centers is warranted.

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DISCUSSION

Dr. Joseph S. Coselli (Houston, Tex.). Dr. Cambria and his associates are to be congratulated for their ongoing efforts in the development and evaluation of techniques for spinal cord preservation in the treatment of patients who have thoracic aortic disease. Despite several reports to the contrary, I concur entirely with the authors' emphasis on the reattachment of intercostal arteries and, consequently, the preserving of direct arterial circulation to the spinal cord. It seems implausible to many of us that if patients with extent II thoracoabdominal aortic aneurysms have their intercostal arteries entirely ignored, there would be no increased risk of postoperative neurologic deficit.

I further agree that the multiplicity of diverse efforts regarding spinal cord protection in centers the world over is a consequence of the multifactorial nature of spinal cord injury, but also reflects how much there is yet to be done and how little we as yet know. The current study lacks, however, the benefits of a prospective randomized trial. The authors at least partially compensate for this by the use of recent same-surgeon controls and, additionally, apply Acher's predictive model equation. I do, however, have some concerns regarding Acher's equation, in that it includes the number of dissections as a variable. Our recent experience, and that of others, no longer identifies chronic dissection as a variable associated with the development of postoperative neurologic deficits. The authors, in their manuscript, reinforce this point despite their use of the equation.

In addition, Acher's model may not reflect a generalized trend in the reduced risk of paraplegia and paraparesis in recently reported series. Applying Acher's equation to 750 thoracoabdominal aortic aneurysms in my own work (219 of which were extent II), the overall predicted risk for paraplegia or paraparesis by calculation with that equation would have been 12.5%, whereas the actual incidence was 5.5%. We have reached a point at which I believe that we have enough experience to no longer include extent III and extent IV aneurysms along with extent I and extent II in models of predictive risk for neurologic deficits.

I have several questions for the authors. Would it not be important to precisely state the incidence of paraplegia in the patients of the various groups, that is, dissection, rupture, etc., as well as the extent for their control series? Do the authors believe that the increase in experience and the difficult-to-define "learning curve" plays a role in the overall improved results? To what factors do the authors attribute their continued 10% mortality rate, which they admit is still somewhat high? The 30-day operative mortality rate for the 750 patients I mentioned previously was 5.3%. The authors have noted that the increased use of the reattachment of intercostal anastomoses was of borderline significance ($p = 0.04$). Is it not possible that this aspect has been understated in its influence on the reduction in the incidence of neurologic deficit?

Finally, the influence of CSF drainage in the literature has received mixed reviews. It is interesting that in the authors' experience with EC, the CSF pressures are actually increased. Could the authors comment on their thoughts regarding CSF drainage alone?

Dr. Richard P. Cambria. Thank you, Dr. Coselli, for your comments and questions, and we certainly acknowledge that they are borne of extensive experience and expertise in the management of these patients.

You asked about the role of the learning curve in improved current results. That factor was indeed acknowledged in an earlier report from our institution, but we would like to think that that learning curve took place somewhat earlier than 1990.

With respect to the overall operative mortality rate, we considered any patient who died during the hospital course, out to and including 60 days, as an operative death, whereas many reports, and including your own discussion, have considered only the 30-day mortality rate. We think that a patient who limps along and dies 6 weeks after operation ought to be included as an overall operative death.

With respect to the possible confounding influence of an apparently more aggressive posture toward intercostal anastomoses in the patients whom we are currently treating, I obviously cannot exclude that factor as a contributor to the improved present results because there was clearly a trend over time at our institution toward more aggressive management of patent intercostal vessels.

With respect to CSF drainage alone, you are certainly aware of the two trials that have apparently shown no benefit for the application of this method alone. And indeed, in the control patients outlined in our report today, that is since 1990, these patients did have CSF drainage, which has been in use at our institution since the late 1980s.

Dr. Anthony J. Comerota (Philadelphia, Pa.). I would like to congratulate Dr. Cambria and his coauthors on their excellent study and presentation. Do you think that the addition of a bypass grafting procedure, either an axillofemoral or atriofemoral bypass, in addition to what you do for spinal cord cooling, would further lower the risk of ischemia? I think that it is intuitive that if you are rushing to reattach the visceral and the renal circulation that you tend to pass up potentially important intercostal vessels. It is also comforting when you doubly clamp the thoracic aorta in some of these extensive aneurysms, in the presence of an axillofemoral bypass, to have pulsatile perfusion in the visceral and in the renal vessels. And I think that would indicate that indeed they are not ischemic at the time, and your true ischemia, for visceral and renal, is when you move the clamp to the infrarenal location in the presence of an axillofemoral bypass.

Dr. Cambria. Thank you, Dr. Comerota, for your comment and question. Essentially you are asking me to resolve the debate between shunters versus nonshunters. We have personally maintained a posture of an expeditious operation with a minimum of adjuncts, such as shunts and bypasses, all of which have their own potential complications. The important component of the epidural cooling technique, of course, is that during the period of cross-clamping the cord itself is relatively protected by the hypothermic milieu.

My principal objection to the sequential clamping technique is that although it looks quite nice in stylized cartoons, I do not believe that it is physically possible to separate with sequential clamping those truly critical intercostal vessels from the visceral vessels, so my criticism of the technique has been that it largely buys one the time required to complete the proximal anastomosis, which in the spectrum of the overall cross-clamp time has been a minimum of that time.

Dr. Peter Gloviczki (Rochester, Minn.). I would like to congratulate Dr. Cambria for the excellent results by his group. We at the Mayo Clinic also have been very enthusiastic about the epidural cooling technique, and we have used epidural cooling in more than 50 cases now. The first question that I would like to ask you concerns the number of patients that are included in your study. Do you think that you have enough patients in your type I and type II groups, which are really prone to have paraplegia? You had 35 patients in that group. We went more than 20 cases before our first patient developed paraplegia. And indeed, now, of the 43 cases that we analyzed, we had 24 thoracoabdominal aortic aneurysms. Paraplegia developed in three patients, giving an incidence of 9%, which is similar to what we observed in a previous series of 201 patients with thoracoabdominal aortic aneurysms. So I'm wondering

whether you think that you have enough patients in the study to conclude that epidural cooling is effective.

My second question concerns the increased spinal pressure. I am concerned that patients in whom paraplegia developed are maybe those who had increased cerebrospinal pressure. I'm wondering whether you found increased pressure in those patients in whom paraplegia developed. In one of our patients who had paraplegia, we measured spinal fluid pressure during cooling to be more than 100 mm Hg.

Finally, my third question concerns the duration of epidural cooling. Your cooling period lasted an average of 200 minutes. It appears that the surgeon's goal should be to decrease the period of cooling to the minimum so that high pressures in the spinal cord can be avoided. Could you tell us about some techniques on how to reduce the cerebrospinal fluid pressure during epidural cooling.

Dr. Cambria. Thanks very much, Peter, for your comments. I would first like to say a word about aneurysm extent, and Dr. Coselli brought this issue up as well. I have been impressed in looking at the literature over the past few years with the imprecision with which these classifications are applied. I attempted to point out in the presentation that a type II designation was reserved for a patient who has the entire descending thoracic aorta resected. It has been my observation that these criteria have been more liberalized in the more recent literature. Many of our patients with type III aneurysm—(some part of the descending thoracic aorta and entire abdominal aorta) constituting our single most common morphologic characteristic of thoracoabdominal aneurysm—had resection of that segment of the aorta from T_8 to L_1 from whence the critical intercostal vessels arise.

With respect to your question about CSF pressure, you noted that you had a patient with a CSF pressure recording of 100 mm Hg or greater. I alluded also in the presentation that the experience with our single very atypical but devastating neurologic deficit caused us to look carefully at the interplay between relative spinal cord perfusion pressure and CSF pressure. To minimize CSF pressure elevations, the epidural infusion should be started early so that it can be started at low rates. It has been our experience that after 40 minutes of cooling we have that segment of the cord most vulnerable to ischemic injury, namely, the lower thoracolumbar cord, at 25° C. The other important thing is to maintain a careful eye on the qualitative aspects of the CSF pressure tracing. The total duration of epidural cooling has run close to 200 minutes, but that is intentional because of the rather slow and gradual way that we prefer to lower the temperature to minimize the increase in CSF pressure. The inference, of course, from our data is that one can tolerate at least doubling of baseline CSF pressures if the hypothermic milieu is provided to that segment of the cord at risk for ischemic injury.

Dr. Brent T. Allen (St. Louis, Mo.). I would like to congratulate Dr. Cambria and his associates for not only developing this technique but also for applying the technique so successfully in their group of patients. We have not had any clinical experience with this method, but we have had some experience in the laboratory. One of the difficulties that we have noted is getting the system to flow properly. My question is, in how many patients did you try this technique but were ultimately unsuccessful either in getting epidural cooling or in having too high of an epidural pressure to use it successfully? Also, how many patients had to have it stopped prematurely because of high epidural pressures?

Dr. Cambria. The question in reference to CSF pressure I think we have just addressed. We maintain an arbitrary 30 to 40 mm Hg gradient between mean arterial and CSF pressure before aortic cross-clamping. At the period of aortic cross-clamping, the segment of the cord vulnerable to ischemic injury is now well cooled.

You also asked about the mechanics. In these 70 patients, two patients' epidural catheters ceased to function after the operation had been commenced, and cooling was accomplished by a rather cumbersome alternate injection and withdrawal by hand directly into the subarachnoid catheter. I would point out that others have experience with continuous perfusion systems into subarachnoid catheters, but we have not used that specific technique. Aborting the infusion because of prohibitively high CSF pressures has been rare.